Journal of Power Sources 240 (2013) 33–41

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Short communication

Research on the heat dissipation performance of battery pack based on forced air cooling

X.M. Xu*, R. He

School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, China

HIGHLIGHTS

- Changing longitudinal battery pack into horizontal battery pack, it could improve the heat dissipation performance by shorting airflow path.
- The heat dissipation performance of battery pack with double "U" type duct basically met the design requirements at different temperatures.
- When the heat dissipation condition was poor, it could reduce the SOC state to satisfy the heat dissipation performance requirements.
- It could reduce the charge and discharge rate to satisfy the heat dissipation performance requirements.
- Comparing with the practical operation condition of battery pack, it met the heat dissipation performance requirements.

ARTICLE INFO

Article history:
Received 26 December 2012
Received in revised form
25 February 2013
Accepted 2 March 2013
Available online 28 March 2013

Keywords:
Battery pack
Forced air cooling
Airflow duct mode
Heat dissipation performance
Charge and discharge rate

ABSTRACT

Electric vehicle cooling modes are divided into air cooling, liquid cooling and phase change material cooling, the air cooling is divided into natural air cooling and forced air cooling. This paper selects the forced air cooling as the study object, and researches the heat dissipation performance of different airflow duct modes, the results indicated that: as considering that changing the longitudinal battery pack into horizontal battery pack, it could improve the heat dissipation performance by shorting airflow path; it increases the contact area for thermal conduction by adding bottom duct, and the area of battery pack top exists natural convection, so the heat dissipation performance of bottom duct mode is more superior; for battery pack with bottom duct mode, it uses the double “U” type duct instead of double “1” type duct in order to improve the heat dissipation performance; when the heat dissipation condition is poor, it could reduce the SOC state or charge & discharge rate to satisfy the heat dissipation performance requirements; as considering the practical operation condition of battery pack with double “U” type duct, it has a large margin of high charge and discharge rate to meet the needs of electric vehicle acceleration or deceleration operation.

It is widely used the forced air cooling as the cooling method of battery pack at home and abroad [1–3], many researchers have carried out the related work: for battery pack arrangement, Takaki [4] separated the forced air cooling into serial airflow and parallel airflow; the forced air cooling system developed by Toyota corporation was the most representative, and the relevant patents were applied [5]; Pan [6] researched the heat dissipation performance of Hybrid-Electric vehicle battery pack by software STAR-CD and ANSYS, and validated by experiments; Fu [7] researched the thermal management system of Ni-MH battery pack; Zhu [8] researched the thermal management system of electric vehicle battery pack, and analyzed the cooling system structure design of Toyota RAV-4 electric vehicle; when the speed of electric vehicle was constant, Liu [9] researched the temperature field of lithium-ion battery pack based on natural air cooling by simulation and experiment. In addition, there are many forced air cooling system of battery pack developed by researchers and manufacturers [10–12], in order to improve the temperature distribution uniformity of battery module.

This paper selects the forced air cooling of battery pack as the study object (the battery pack has a total of 48 batteries, and includes 4 battery modules with 2 parallels and 6 series), and researches the heat dissipation performance of different airflow duct modes, in order to offer a reference basis for heat flow field characteristic analysis of battery pack and airflow duct mode choosing.

* Corresponding author. Tel.: +86 13795269280.
E-mail address: xuxiaoming3777@163.com (X.M. Xu).

0378-7753/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jpowsour.2013.03.004

Table 1
Thermal physical parameters of 55Ah lithium-ion battery.

Battery component	Density $(kg(m^3)^{-1})$	Thermal conductivity coefficient $(W(m\ K)^{-1})$	Specific heat capacity $(J(kg\ K)^{-1})$
Electric core	2123	30.6	913
The positive pole	2719	202.4	871
The negative pole	8978	387.6	381
The diaphragm	1008	0.3344	1978
Shell	8193	14.7	439.3

1. Thermal power determination test of 55Ah lithium-ion battery on charge and discharge processing

1.1. Thermal physical parameters of 55Ah lithium-ion battery

Table 1 shows the thermal physical parameters of 55Ah lithium-ion battery: the density of electric core is 2123 $kg(m^3)^{-1}$, the thermal conductivity coefficient is 30.6 $W(m\ K)^{-1}$, and the specific heat capacity is 913 $J(kg\ K)^{-1}$.

1.2. Thermal power determination test of 55Ah lithium-ion battery on charge and discharge processing

Fig. 1 shows the arrangement of temperature measuring point and the design of thermal insulation with 55Ah lithium-ion battery, including 2 measuring points on bottom and 3 measuring points on side wall, heat insulation box has three layers of insulating material surround, in order to ensure good thermal insulation performance.

Calorific value calculation formula is as follows:

$$Q = c_p m \Delta T \tag{1}$$

Q means calorific value; c_p means specific heat capacity; m means quality; ΔT means temperature rising.

It could be introduced into the thermal power calculation formula by Formula (1) as follows:

$$P = \frac{c_p m \Delta T}{t} \tag{2}$$

P means thermal power; t means time.

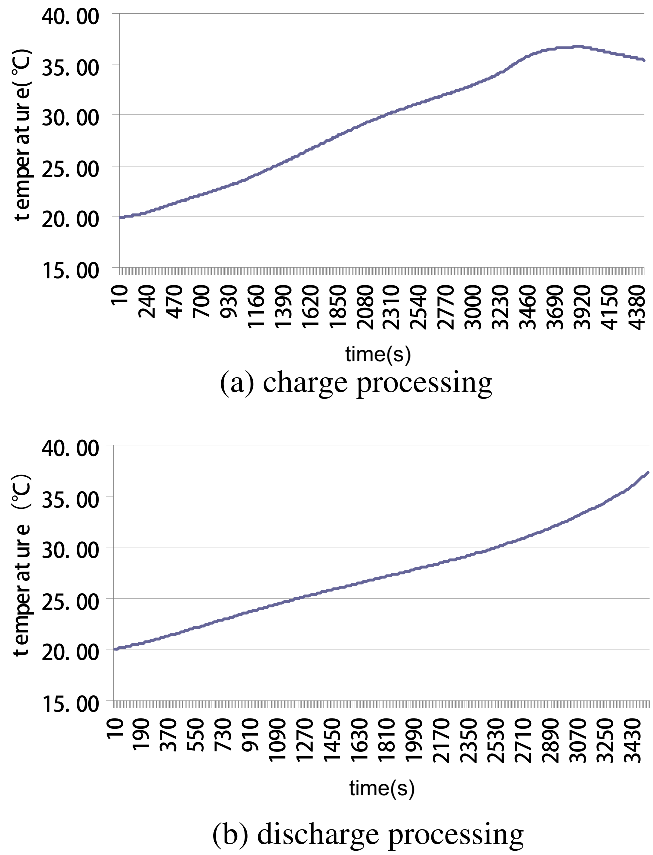
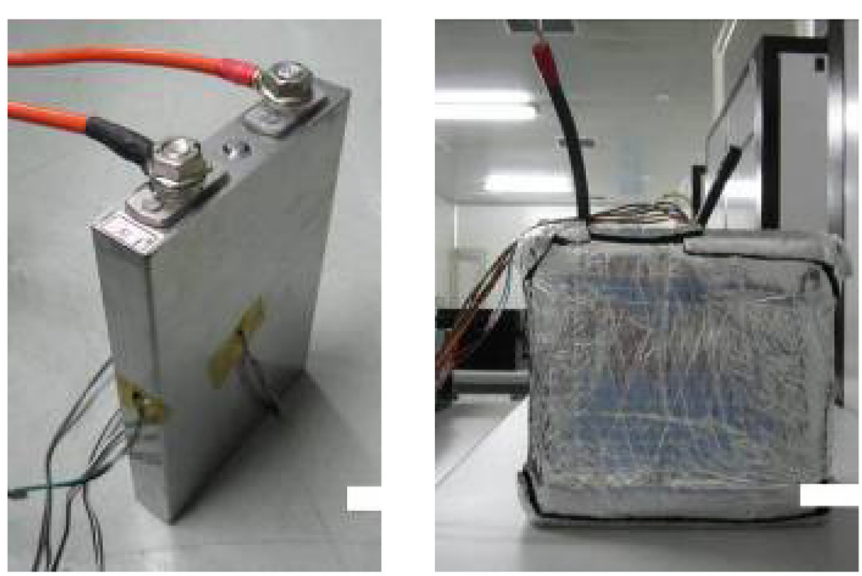


Fig. 2. When the environmental temperature is 20 °C, the average temperature curve of 55Ah lithium-ion battery on charge and discharge processing.

Constant temperature box is set to suitable temperature, the experimental processing is as follows: firstly, setting 1C charge rate up to 3.65 V; secondly, turning to constant-voltage charge, until 0.05 C cutoff; thirdly, setting 1C discharge rate down to 2.50 V.



(a) Temperature measuring point (b) Heat insulation box

Fig. 1. The arrangement of temperature measuring point and the design of thermal insulation with 55Ah lithium-ion battery.

When the environment temperature is 20 °C, and the charge & discharge rate is 1C, Fig. 2 shows the average temperature curve of 55Ah lithium-ion battery at 100% SOC state, combining with thermal physical parameters of 55Ah lithium-ion battery, it could be obtained the thermal power on charge and discharge processing. As could be seen from Table 2, the average thermal power of 55Ah lithium-ion battery is 6.51 W at 20 °C, 5.36 W at 27 °C, and 4.66 W at 40 °C, it is obvious that the average thermal power of 55Ah lithium-ion battery decreased along with environment temperature rising.

As considering that the constant temperature box was not completely insulated, therefore, the measured average temperature rising of lithium-ion battery is less than the temperature rising of actual thermal insulation; it means the calculation value of thermal power is also slightly lower than the actual value. The thermal power of battery monomer on charge and discharge processing is the reference for the heat source setting on simulation calculation.

2. Calculation method, boundary condition and heat dissipation performance index

2.1. Mathematical model

Normally, the maximum velocity of airflow in battery pack is less than 400 km h^{-1}, it means less than 1/3 sound velocity, so the airflow in battery pack could be considered to incompressible flow, and the physical parameters of airflow are constant number. Combining with the phenomenon of air separation by complex structure of battery pack, it should be considered to the turbulent processing. The control equations are as follows:

Continuity equation:

$$\nabla \cdot \bar{v} = 0 \tag{3}$$

Momentum conservation equation:

$$\frac{\partial \bar{v}}{\partial t} + (\bar{v} \cdot \nabla)\bar{v} = -\frac{\nabla p}{\rho} + \frac{\mu}{\rho}\nabla^2 \bar{v} \tag{4}$$

Energy conservation equation:

$$\rho \cdot c_p \cdot \left(\frac{\partial E}{\partial t} + u \cdot \frac{\partial E}{\partial x} + v \cdot \frac{\partial E}{\partial y} + w \cdot \frac{\partial E}{\partial z} \right) = \lambda \cdot \left(\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} \right) \tag{5}$$

$\bar{v}$ means velocity vector; t means time; p means pressure; ρ means density; μ means viscosity coefficient; c_p means specific heat; E means total energy; u, v and w respectively mean the velocity of x, y and z direction; λ means thermal conductivity coefficient.

2.2. Calculation method

Three-dimensional incompressible Navier–Stokes equations and Standard k–ε model are used on simulation, and SIMPLEC method is adapted to iterate.

Table 2
At different environment temperatures, thermal power of 55Ah lithium-ion battery on charge and discharge processing (W).

Temperature (°C)	The average thermal power on charge processing	The average thermal power on discharge processing	The average thermal power on charge and discharge processing
20	5.42	7.60	6.51
27	4.36	6.35	5.36
40	3.56	5.76	4.66

2.3. Boundary condition

The air-inlet is free inlet boundary condition, and the pressure is standard atmospheric pressure. The air-outlet is fan outlet boundary condition, and Fig. 3 shows the curve between fan pressure difference and flow rate: when the pressure difference between air-inlet and air-outlet is 125 Pa, the flow rate is 0.0028 m^3 s^{-1} (10.8 m^3 h^{-1}); when the pressure difference between air-inlet and air-outlet is 0 Pa, the flow rate is 0.0083 m^3 s^{-1} (29.9 m^3 h^{-1}), the battery pack includes two fans. It uses no-slip boundary condition as wall surface, and the speed is zero. The heat power of lithium-ion battery depends on the given specific example.

2.4. Heat dissipation performance index

Assessing the heat dissipation performance of battery pack cooling system has two main indexes: the maximum temperature rising and temperature difference (it defines the maximum difference value between battery pack temperature and environmental temperature as maximum temperature rising, and the maximum value of battery pack internal temperature difference as maximum temperature difference). If the maximum temperature rising is too big, it means the environment temperature is relatively poor for battery pack working, and the heat generated by battery pack could not be effectively taken away through the cooling system; if the maximum temperature difference is too big, it means the temperature distribution uniformity of battery pack is poor, so the purpose of battery pack cooling system design should be set to reduce the maximum temperature rising and temperature difference. The heat dissipation performance design requirement of battery pack cooling system: the maximum temperature rising is less than 10 °C, and the maximum temperature difference is less than 5 °C.

3. Heat flow field analysis with different airflow duct modes

3.1. Heat flow field analysis with longitudinal battery pack

The air-inlet is on the opposite position of fan, Fig. 4(a) shows that the high temperature area of longitudinal battery pack is in the central, and near the air-outlet; the temperature of air-inlet is relatively low. Airflow is inhaled from the air-inlet, and heated by battery pack, then the temperature of airflow rises, it eventually leads the airflow cooling capacity to decrease. Therefore, the purpose of reasonable airflow duct design should improve the airflow cooling capacity, especially near air-outlet, it is more important to improve airflow passing ability in order to decrease the temperature of

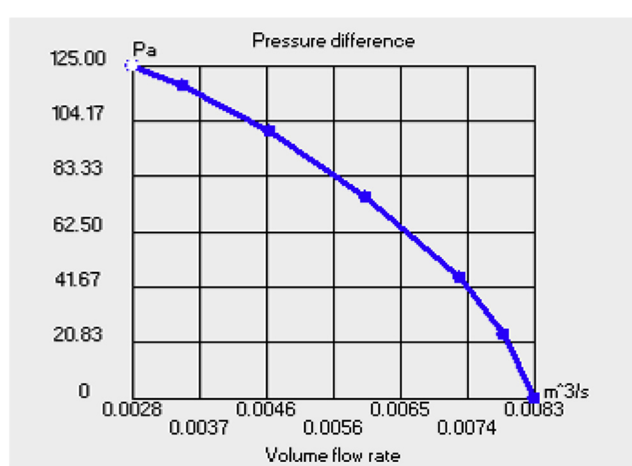


Fig. 3. The curve between fan pressure difference and flow rate.

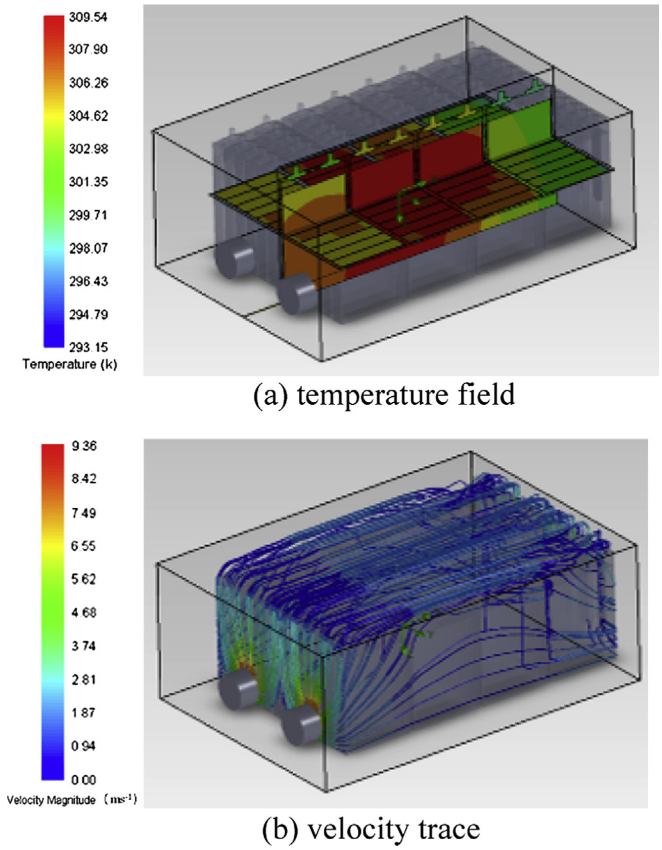


Fig. 4. The temperature field and velocity trace of longitudinal battery pack at 20 °C.

airflow, as could be seen from Fig. 4(b), the airflow mainly passes the top of battery pack but not through both sides, and near air-outlet, the speed of airflow is relatively more high. Table 3 shows the heat flow field data of longitudinal battery pack at different environmental temperatures, the flow rate and the average pressure drop between air-inlet & air-outlet both decrease along with environmental temperature increasing. For the same airflow duct (it means that airflow cooling capacity decreases along with flow rate reducing), the heat power of lithium-ion battery reduces along with environmental temperature increasing, it eventually leads the maximum temperature rising and temperature difference of battery pack to reduce along with environment temperature increasing. Among them, the maximum temperature rising of battery pack at 40 °C is lower by 26.7% and 11.6% than 20 °C and 27 °C; the maximum temperature difference of battery pack at 40 °C is lower by 27.6% and 12.2% than 20 °C and 27 °C. When the charge and discharge rate is 1C, the heat dissipation performance of longitudinal battery pack could not meet the design requirements at all environment temperatures.

3.2. Heat flow field analysis with horizontal battery pack

It could improve the heat dissipation performance by shorting the airflow path in order to improve airflow passing ability. For example, it could change the above longitudinal battery pack into horizontal battery pack, and the air-inlet is also on the opposite position of fan. Fig. 5 shows that the high temperature area of horizontal battery pack is in the central, and near the air-outlet; the low temperature area is on the top of battery pack, and near the air-inlet. Combination with velocity trace distribution, it could be seen that the airflow along with the top and two sides of horizontal battery pack is uniform, then avoiding the problem of little airflow passing through two sides of battery pack. As could be seen from Table 4, the flow rate and the average pressure drop between air-inlet & air-outlet both decrease along with environmental temperature increasing, and the maximum temperature rising and temperature difference of battery pack reduce along with environment temperature increasing too. Among them, the maximum temperature rising of horizontal battery pack at 40 °C is lower by 26.2% and 11.1% than 20 °C and 27 °C; the maximum temperature difference of horizontal battery pack at 40 °C is lower by 25.9% and 10.8% than 20 °C and 27 °C. When the charge and discharge rate is 1C, the heat dissipation performance of horizontal battery pack could not meet the design requirements at all environment temperatures, comparing with longitudinal battery pack, the heat dissipation performance of horizontal battery pack has improved.

Table 3
The heat flow field data of longitudinal battery pack at different environmental temperatures.

Environmental temperature (°C)	20	27	40
Flow rate ($m^3\ h^{-1}$)	34.15	33.50	32.21
The maximum temperature rising (°C)	16.39	13.58	12.01
The maximum temperature difference (°C)	12.00	9.90	8.69
The average pressure drop (Pa)	76	75	73

3.3. Heat flow field analysis with bottom airflow duct

The airflow of two above duct modes (longitudinal battery pack and horizontal battery pack) is directly contacted with the battery module, but could not meet the heat dissipation performance design requirements. It arranges the airflow duct on the battery

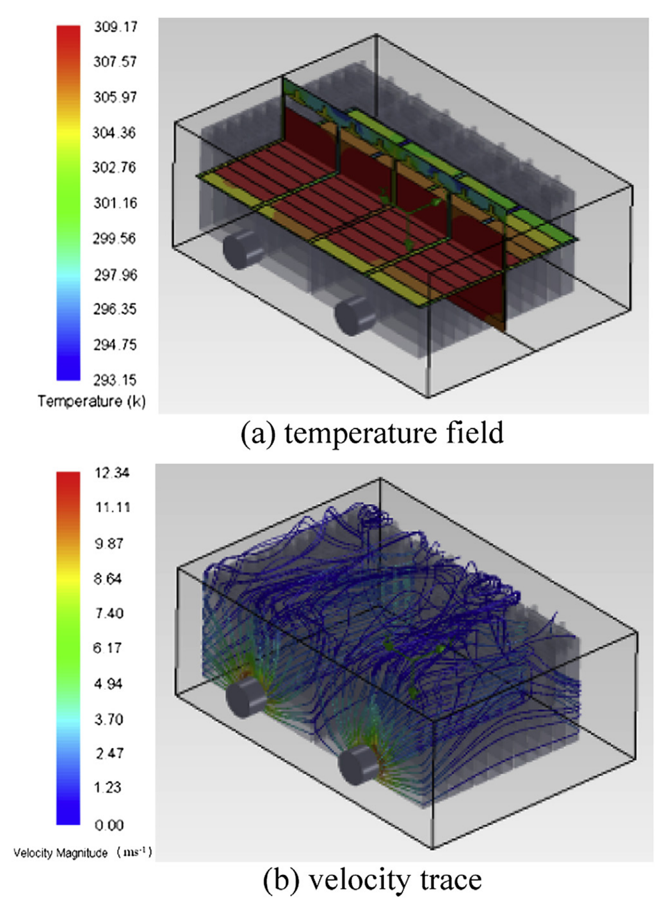


Fig. 5. The temperature field and velocity trace of horizontal battery pack at 20 °C.

Table 4
The heat flow field data of horizontal battery pack at different environmental temperatures.

Environmental temperature (°C)	20	27	40
Flow rate (m^3 h^{-1})	34.77	34.12	32.80
The maximum temperature rising (°C)	16.02	13.31	11.83
The maximum temperature difference (°C)	11.05	9.18	8.19
The average pressure drop (Pa)	89	87	84

Table 5
The heat flow field data of bottom airflow duct at different environmental temperatures.

Environmental temperature (°C)	20	27	40
Flow rate (m^3 h^{-1})	7.26	7.11	6.82
The maximum temperature rising (°C)	10.36	8.55	7.50
The maximum temperature difference (°C)	4.34	3.58	3.14
The average pressure drop (Pa)	60	57	50

pack bottom, then the airflow is not directly contacted with the battery module, this paper does a research on the heat dissipation performance of battery pack with bottom airflow duct. Fig. 6 shows the temperature field and velocity trace of battery pack with bottom airflow duct at 20 °C, as could be seen that the temperature of battery pack bottom is low, and the temperature of area near the air-inlet is less than far away from the air-inlet, it shows that the cooling performance of airflow entering the duct is excellent at first, after convection heat transfer, the cooling performance of airflow is decreased by battery pack heating, it leads the temperature of area far away from air-inlet to more high than other place. As could be seen from Table 5, the flow rate and the average pressure drop between air-inlet & air-outlet both decrease along with environmental temperature increasing, and the maximum temperature rising and temperature difference of battery pack reduce along with environment temperature increasing too. Among them, the maximum temperature rising of horizontal battery pack at 40 °C is lower by 27.6% and 12.3% than 20 °C and 27 °C; the maximum temperature difference of horizontal battery pack at 40 °C is lower by 27.6% and 12.2% than 20 °C and 27 °C. When the charge and discharge rate is 1C, the heat dissipation performance of battery pack with bottom airflow duct meets the design requirements at 27 °C and 40 °C.

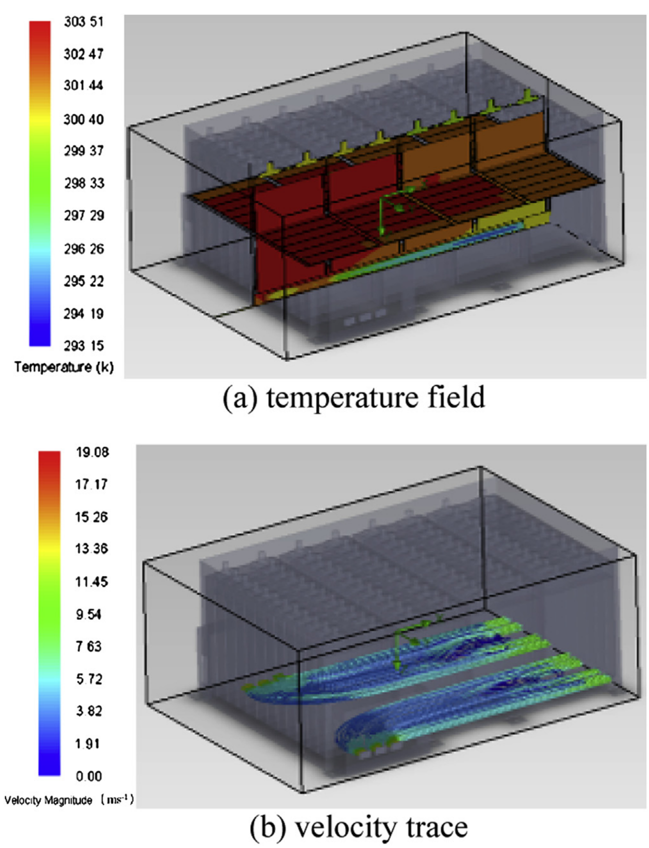


Fig. 6. The temperature field and velocity trace of bottom airflow duct at 20 °C.

3.4. The comparisons of heat flow field characteristics with different airflow duct modes

When the environmental temperature is 20 °C, Table 6 shows the comparisons of heat flow field characteristics with different airflow duct modes, it could be seen that the maximum temperature rising and temperature difference of battery pack with bottom duct mode are minimum, and that of the longitudinal battery pack are maximum. Among them, the maximum temperature rising of battery pack with bottom duct mode is lower by 36.8% and 35.3% than longitudinal battery pack and horizontal battery pack; the maximum temperature difference of battery pack with bottom duct mode is lower by 63.8% and 60.7% than longitudinal battery pack and horizontal battery pack. Although the airflow of bottom duct mode is low, but it increases the contact area for thermal conduction, and the area of battery pack top exists natural convection, so the heat dissipation performance of bottom duct mode is still superior. The order of heat dissipation performance from low to high is as follows: longitudinal battery pack, horizontal battery pack, and battery pack with bottom duct mode. When the charge and discharge rate is 1C, and the environmental temperature is 20 °C, the heat dissipation performance of battery pack with all airflow duct modes could not meet the design requirements, but the maximum temperature rising of battery pack with bottom duct mode is 10.36 °C, and it approaches the design requirements.

4. The comparisons of heat dissipation performance with different bottom airflow ducts

4.1. Heat flow field analysis after bottom airflow duct modified

For battery pack with bottom duct mode, it uses the double "U" type duct instead of double "1" type duct. Fig. 7 shows the temperature field and velocity trace of battery pack with double "U" type duct at 20 °C, comparing with the double "1" type duct, the temperature field distribution of battery pack is more uniform. As could be seen from Table 7, the flow rate and the average pressure drop between air-inlet & air-outlet both decrease along with environmental temperature increasing, and the maximum temperature rising and temperature difference of battery pack reduce

Table 6
When the environmental temperature is 20 °C, the comparisons of heat flow field characteristics with different airflow duct modes.

	Longitudinal battery pack	Horizontal battery pack	Battery pack with bottom duct mode
Flow rate (m^3 h^{-1})	34.15	34.77	7.26
The maximum temperature rising (°C)	16.39	16.02	10.36
The maximum temperature difference (°C)	12.00	11.05	4.34
The average pressure drop (Pa)	76	89	60

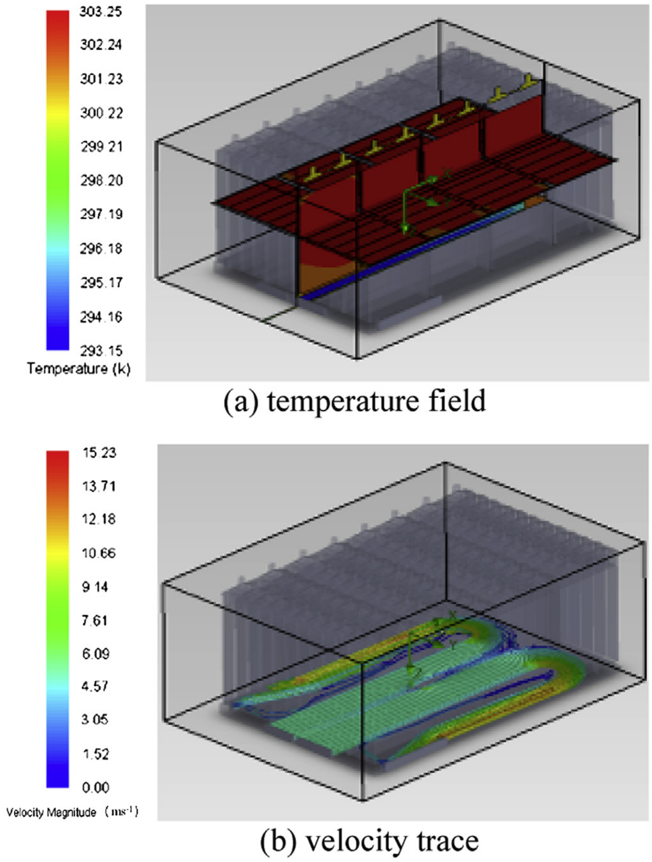


Fig. 7. The temperature field and velocity trace of bottom airflow duct modified at 20 °C.

along with environment temperature increasing too. When the charge and discharge rate is 1C, it improves the heat dissipation performance of the forced air cooling system by changing double "1" type duct into double "U" type duct at different environment temperatures.

4.2. The comparisons of heat flow field characteristics with different bottom airflow ducts

When the environmental temperature is 20 °C, Table 8 shows the comparisons of heat flow field characteristics with different bottom duct modes, comparing with the double "1" type duct, the flow rate and the average pressure drop between air-inlet & air-outlet with double "U" type duct are more high, and the maximum temperature rising and temperature difference are more low. Among them, the maximum temperature rising of battery pack with double "U" type duct is lower by 2.5% than double "1" type duct, and the maximum temperature difference of battery pack with double "U" type duct is lower by 24.2% than double "1" type duct. When the charge and discharge rate is 1C, and the environmental temperature is 20 °C, the maximum temperature rising of

Table 7
The heat flow field data of bottom airflow duct modified at different environmental temperatures.

Environmental temperature (°C)	20	27	40
Flow rate ($m^3\ h^{-1}$)	7.44	7.29	6.99
The maximum temperature rising (°C)	10.10	8.28	7.33
The maximum temperature difference (°C)	3.29	2.67	2.42
The average pressure drop (Pa)	62	59	53

Table 8
When the environmental temperature is 20 °C, the comparisons of heat flow field characteristics with different bottom airflow ducts.

	The double "1" type duct	The double "U" type duct
Flow rate ($m^3\ h^{-1}$)	7.26	7.44
The maximum temperature rising (°C)	10.36	10.10
The maximum temperature difference (°C)	4.34	3.29
The average pressure drop (Pa)	60	62

battery pack with double "U" type duct is 10.10 °C, it basically meets the design requirement.

5. Heat flow field analysis at different SOC states

5.1. The thermal power of 55Ah lithium-ion battery at different SOC states

When the environment temperature is 20 °C, and the charge & discharge rate is 1C, Fig. 8 shows the average temperature curve of 55Ah lithium-ion battery at 70% SOC state, Table 9 shows the thermal power of 55Ah lithium-ion battery at different SOC states. The average thermal power of 55Ah lithium-ion battery is 6.25 W at 70% SOC state, 6.87 W at 80% SOC state, 7.19 W at 90% SOC state, and 6.51 W at 100% SOC state.

5.2. Heat flow field analysis at 70% SOC state

Fig. 9 shows the temperature field and velocity trace of battery pack with double "U" type duct at 70% SOC state, comparing with

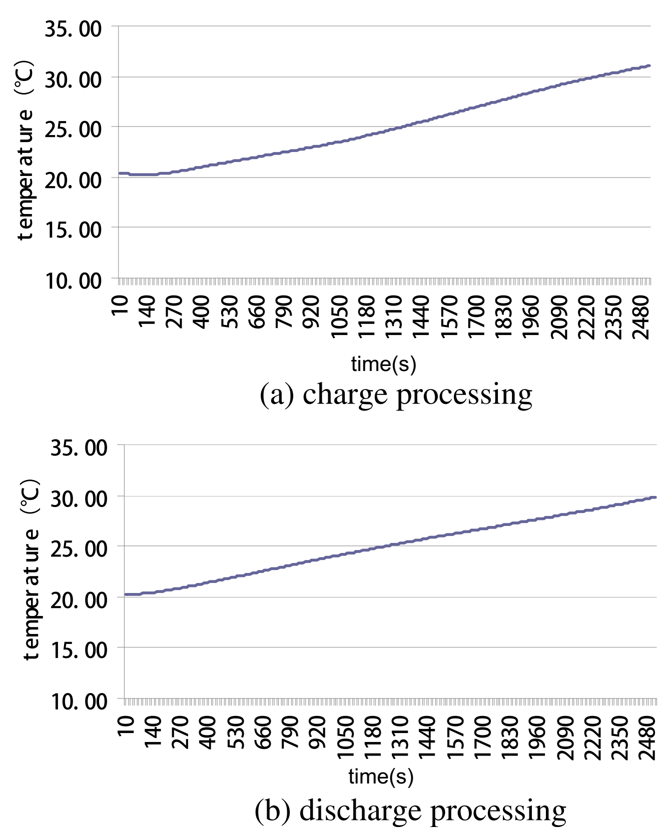


Fig. 8. The average temperature curve of 55Ah lithium-ion battery at 70% SOC state.

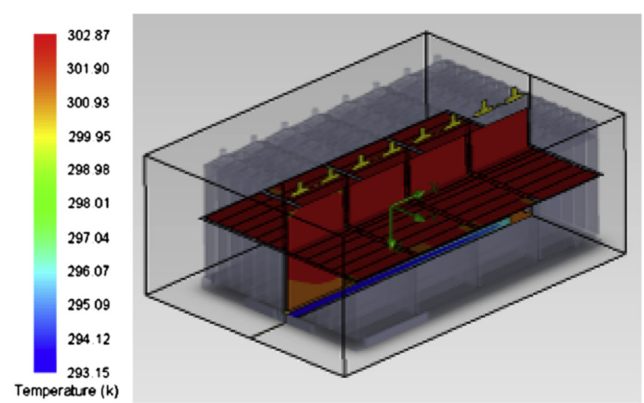
Table 9
On charge and discharge processing, the thermal power of 55Ah lithium-ion battery at different SOC states (W).

SOC state	The average thermal power on charge processing	The average thermal power on discharge processing	The average thermal power on charge and discharge processing
70%	6.60	5.90	6.25
80%	6.86	6.88	6.87
90%	7.11	7.27	7.19
100%	5.42	7.60	6.51

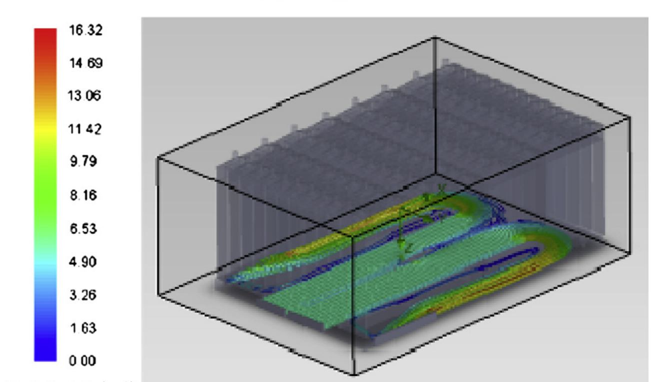
100% SOC state, the temperature field distribution and velocity trace are basically the same except the numerical value. As could be seen from Table 10, the maximum temperature rising and temperature difference of battery pack are 9.72 °C and 3.17 °C.

5.3. The comparisons of heat flow field characteristics at different SOC states

Table 11 shows the comparisons of battery pack heat flow field characteristics with double "U" type duct at different SOC states, as could be seen that the flow rate and the average pressure drop between air-inlet & air-outlet are the same, the maximum temperature rising and temperature difference of battery pack at 70% SOC state are minimum, and that of 90% SOC state are maximum, the maximum temperature rising and temperature difference of battery pack at 100% SOC state are between 70% and 80% SOC state. When the charge and discharge rate is 1C, and the environmental temperature is 20 °C, the heat dissipation performance of battery



(a) temperature field



(b) velocity trace

Fig. 9. The temperature field and velocity trace of battery pack with double "U" type duct at 70% SOC state.

Table 10
The data of heat flow field with double "U" type duct at 70% SOC state.

Parameter	Date
Flow rate (m^3 h^{-1})	7.44
The maximum temperature rising (°C)	9.72
The maximum temperature difference (°C)	3.17
The average pressure drop (Pa)	62

pack with double "U" type duct could meet the design requirements only by 70% SOC state. So if the heat dissipation condition is poor, it could reduce the SOC state to satisfy the heat dissipation performance requirements of battery pack with forced air cooling system.

6. Heat flow field analysis at different charge and discharge rates

6.1. The thermal power of 55Ah lithium-ion battery at different charge and discharge rates

When the environment temperature is 20 °C, and the SOC state is 100%, Fig. 10 shows the average temperature curve of 55Ah lithium-ion battery at 0.6C charge and discharge rate, Table 12 shows the thermal power of 55Ah lithium-ion battery at different charge and discharge rates. The average thermal power of 55Ah lithium-ion battery is 3.42 W at 0.6C charge and discharge rate, 5.00 W at 0.8C charge and discharge rate, 6.51 W at 1C charge and discharge rate, 8.44 W at 1.2C charge and discharge rate, 12.83 W at 1.5C charge and discharge rate, and 19.17 W at 2C charge & discharge rate, it is obvious that the average thermal power of 55Ah lithium-ion battery increases along with charge and discharge rate.

6.2. Heat flow field analysis at 0.6C charge and discharge rate

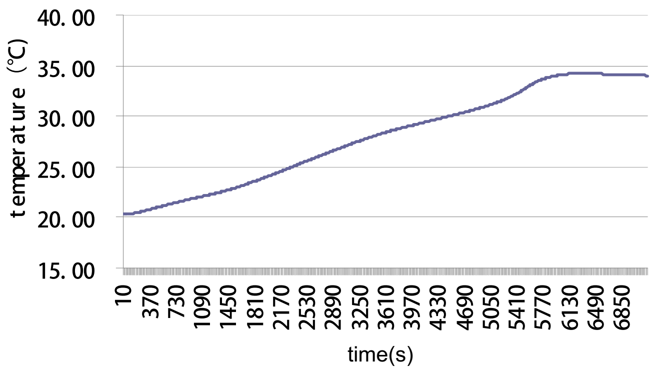
Fig. 11 shows the temperature field and velocity trace of battery pack with double "U" type duct at 0.6C charge and discharge rate, comparing with 1C charge and discharge rate, the temperature field distribution and velocity trace are basically the same except the numerical value. As could be seen from Table 13, the maximum temperature rising and temperature difference of battery pack are 5.29 °C and 1.70 °C.

6.3. The comparisons of heat flow field characteristics at different charge and discharge rates

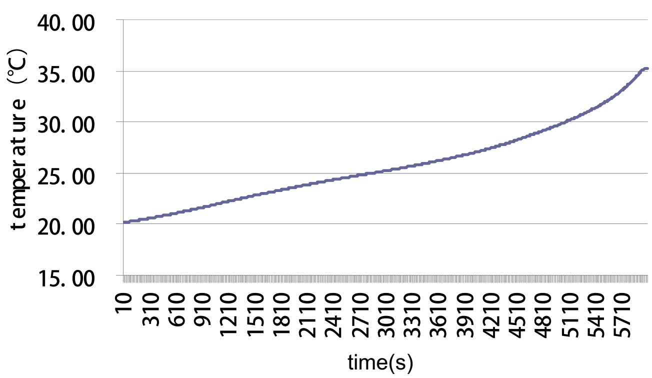
Table 14 shows the comparisons of battery pack heat flow field characteristics with double "U" type duct at different charge and discharge rates, as could be seen that the flow rate and the average pressure drop between air-inlet & air-outlet both decrease along with charge and discharge rate increasing, while the maximum temperature rising and temperature difference of battery pack increase. Among them, the maximum temperature rising of battery pack at 0.6 charge and discharge rate is lower by 32%, 47.6%, 59.6%, 73.2% and 82.2% than 0.8C, 1C, 1.2C, 1.5C and 2C; the maximum temperature difference of battery pack at 0.6 charge and discharge rate is lower by 32.8%, 48.3%, 60.3%, 73.4% and 82.5% than 0.8C, 1C, 1.2C, 1.5C and 2C. When the charge and discharge rate is 0.6C or 0.8C, and the environmental temperature is 20 °C, the heat dissipation performance of battery pack with double "U" type duct could meet the design requirements. So if the heat dissipation condition is poor, it could reduce the charge and discharge rate to satisfy the heat dissipation performance requirements of battery pack with forced air cooling system.

Table 11
The comparisons of battery pack heat flow field characteristics with double "U" type duct at different SOC states.

SOC state	Flow rate ($m^3 h^{-1}$)	The maximum temperature rising (°C)	The maximum temperature difference (°C)	The average pressure drop (Pa)
70%	7.44	9.72	3.17	62
80%	7.44	10.69	3.49	62
90%	7.44	11.08	3.57	62
100%	7.44	10.10	3.29	62

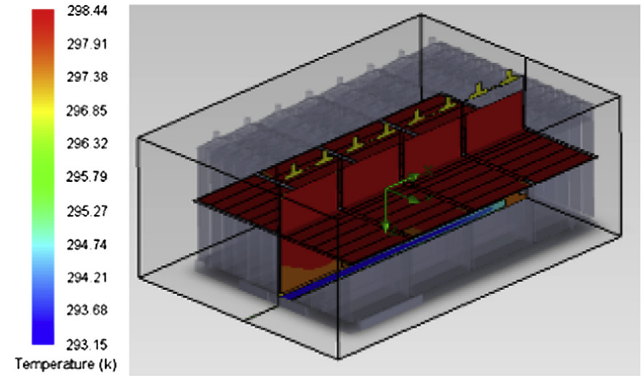


(a) charge processing

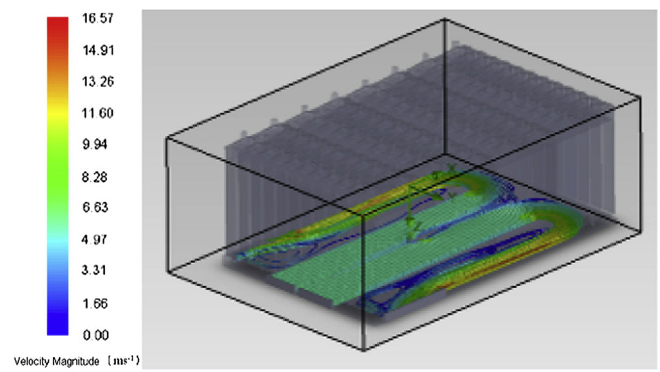


(b) discharge processing

Fig. 10. The average temperature curve of 55Ah lithium-ion battery at 0.6C charge and discharge rate.



(a) temperature field



(b) velocity trace

Fig. 11. The temperature field and velocity trace of battery pack with double "U" type duct at 0.6C charge and discharge rate.

Table 13
The data of heat flow field with bottom duct changing at 0.6C charge and discharge rate.

Parameter	Date
Flow rate ($m^3 h^{-1}$)	7.46
The maximum temperature rising (°C)	5.29
The maximum temperature difference (°C)	1.70

7. Heat dissipation performance analysis with practical operation condition

Fig. 12 shows the curve of electric current following the battery pack work (battery pack work time is 3000 s), as considering the practical operation condition of battery pack is very complicated, it is separately statistics for charge and discharge processing. As could be seen from Table 15, basing on the practical operation of battery pack, the average charge rate is 0.51C, and the average heat power of lithium-ion battery is 2.06 W; the average discharge rate is 0.80C, and the average heat power of lithium-ion battery is 5.69 W.

When the environmental temperature is 20 °C, it uses the battery pack with double "U" type duct as analysis object. Fig. 13 shows the curve of temperature rising and temperature difference following the battery pack practical work, it could be seen that the maximum temperature rising of battery pack is 6.50 °C, and the maximum temperature difference of battery pack is 1.96 °C. As

Table 12
The thermal power of 55Ah lithium-ion battery at different charge and discharge rates (W).

Charge and discharge rate	The average thermal power on charge processing	The average thermal power on discharge processing	The average thermal power on charge and discharge processing
0.6C	2.95	3.89	3.42
0.8C	4.31	5.69	5.00
1C	5.42	7.60	6.51
1.2C	6.62	10.25	8.44
1.5C	10.06	15.60	12.83

Table 14
The comparisons of battery pack heat flow field characteristics with double "U" type duct at different charge and discharge rates.

Charge and discharge rate	Flow rate ($m^3 h^{-1}$)	The maximum temperature rising (°C)	The maximum temperature difference (°C)	The average pressure drop (Pa)
0.6C	7.46	5.29	1.70	64
0.8C	7.45	7.78	2.53	63
1C	7.44	10.1	3.29	62
1.2C	7.41	13.10	4.28	62
1.5C	7.35	19.76	6.38	62
2C	7.29	29.72	9.73	61

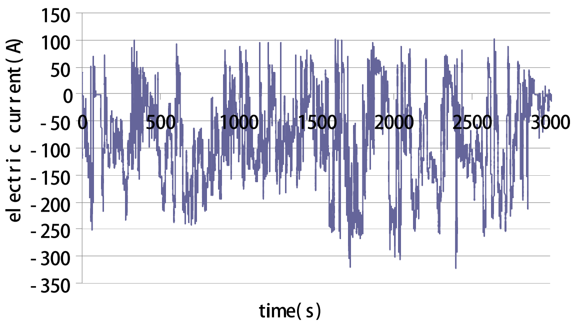


Fig. 12. The curve of electric current following the battery pack work.

Table 15
Practical operation condition of battery pack.

	Charge processing	Discharge processing
The average electric current (A)	56.05	87.88
Time (S)	513	2487
Charge and discharge rate	0.51C	0.80C
The average heat power (W)	2.06	5.69

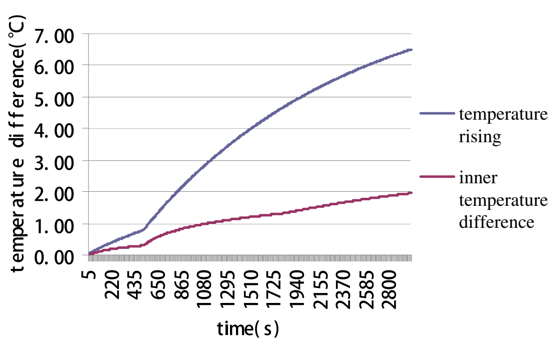


Fig. 13. The curve of temperature rising and temperature difference following the battery pack practical work.

considering the practical operation condition of battery pack, the heat dissipation performance of battery pack with double "U" type duct could meet the design requirements, and it has a large margin of high charge and discharge rate to meet the needs of electric vehicle acceleration or deceleration operation.

8. Conclusion

Through the above research, the conclusions are as follows:

(1) As considering that changing the longitudinal battery pack into horizontal battery pack, it could improve the heat dissipation performance by shorting the airflow path, but the heat dissipation performance of horizontal battery pack could not meet the design requirements at all environment temperatures; it increased the contact area for thermal conduction by adding bottom duct, and the area of battery pack top existed natural convection, so the heat dissipation performance of bottom duct mode was more superior;

(2) For battery pack with bottom duct mode, it used the double "U" type duct instead of double "1" type duct. Comparing with the double "1" type duct, the temperature field distribution of battery pack with double "U" type duct was more uniform, and the maximum temperature rising and temperature difference of battery pack were more low, it improved the heat dissipation performance of the forced air cooling system. The heat dissipation performance of battery pack with double "U" type duct basically met the design requirements at different environment temperatures;

(3) It was comparison of battery pack heat flow field characteristics with double "U" type duct at different SOC states, the flow rate of battery pack at 70% SOC state was maximum. For the maximum temperature rising and temperature difference, the battery pack at 70% SOC state was minimum, 90% SOC state was maximum, and 100% SOC state was between 70% and 80% SOC state. When the heat dissipation condition was poor, it could reduce the SOC state to satisfy the heat dissipation performance requirements of battery pack with forced air cooling system;

(4) It was comparison of battery pack heat flow field characteristics with double "U" type duct at different charge and discharge rates, the flow rate and the average pressure drop between air-inlet & air-outlet both decreased along with charge and discharge rate increasing, while the maximum temperature rising and temperature difference of battery pack rose, so it could reduce the charge and discharge rate to satisfy the heat dissipation performance requirements of battery pack with forced air cooling system;

(5) Comparing with the practical operation condition of battery pack, it statistically obtained that the average heat power of lithium-ion battery on charge processing was 2.06 W, and the average heat power of lithium-ion battery on discharge processing was 5.69 W. Comparing with simulation calculation, the maximum temperature rising of battery pack was 6.50 °C, and the maximum temperature difference of battery pack was 1.96 °C, it met the heat dissipation performance requirements of battery pack with forced air cooling system.

In conclusion, the battery pack with double "U" type duct could satisfy the heat dissipation performance requirements with various conditions (including environmental temperature, SOC state, charge and discharge rate). As considering the practical operation condition of battery pack, it had a large margin of high charge and discharge rate to meet the needs of electric vehicle acceleration or deceleration operation, therefore, the battery pack with double "U" type duct could be the first chosen for battery pack airflow duct mode.

References

[1] B. Otmar, G. Guenter, Systems for hybrid cars, Journal of Power Sources 127 (2004) 8–15.
[2] S.A. Khateeb, S. Amiruddin, M. Farid, Thermal management of Li-ion battery with phase change material for electric scooters: experimental validation, Journal of Power Sources 142 (2005) 345–352.
[3] S. Rami, R. Kizilel, J.R. Selman, et al., Active (air-cooled) vs passive (phase change material) thermal management of high power lithium-ion packs: limitation of temperature rise and uniformity of temperature distribution, Journal of Power Sources 182 (2008) 630–638.
[4] A. Takaki, N. Toyoaki, H. Hideaki, et al., Development of a High-power Battery Cooling System for Series HEVs, EVS-15, Belgium, Brussels, 1998.
[5] W. Osamu, Kanagawa, Battery Cooling Structure. US: 06613472, Tokyo R&D Co, 2003, 10.
[6] H.B. Pan, J.H. Zhao, X.Z. Feng, et al., Use of simulation technology on the construction design of nickel hydride metal piles, Chinese Journal of Mechanical Engineering 41 (12) (2005) 58–61.
[7] Z.Y. Fu, C.T. Lin, Q.S. Chen, Key technologies of thermal management system for EV battery packs, Journal of Highway and Transportation Research and Development 22 (3) (2005) 119–123.
[8] X.T. Zhu, Study in Wind Cooling System for RAV-4 EV Packs, Nanjing University of Aeronautics and Astronautics, Nanjing, China, 2007.
[9] Z.J. Liu, G.F. Lin, D.T. Qin, et al., A study on the temperature field of lithium-ion battery pack in an electric vehicle and its structural optimization, Automotive Engineering 34 (1) (2012) 80–84.
[10] R. Kiziel, A. Lateef, M.M. Farid, et al., Passive control of temperature excursion and uniformity in high-energy Li-ion battery packs at high current and ambient temperature, Journal of Power Sources 183 (2008) 370–375.
[11] Y.J. Zhang, J.M. Xie, et al., The Arrangement Mode of Battery Pack Cooling Mechanism. CN: 1401511A, Tsinghua University, 2002, 9.
[12] G.C. Li, The Heat Dissipation Device of Power Battery Pack. CN: 2660686Y (2003), 10.